Recent advances in the optical control of insect pests using light and color

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ABSTRACT

Technologies employing "light pest control" are becoming an increasingly effective tool in IPM. Until the 1990s, traps using fluorescent tubes and moth-repellent lights using yellow sodium lamps were developed and employed widely. In the 2000s, light-emitting diodes (LEDs) capable of emitting monochromatic light with high luminous efficiency were developed and hence enhanced the potential of light pest control. Simultaneously, numerous studies concerning insect neurophysiology and neuroethology were achieved with new information, such as the spectral sensitivity of insect compound eye and the response behavior to a specific wavelength in many species. These efforts led to the discovery of new biological phenomenon, called the light response reactions. Advances in this area of research in recent years have been astonishing, which motivated the promising study of new light pest control technologies.

Keywords: agriculture, integrated pest management, optical control

INTRODUCTION

Awareness of food safety and security has increased among consumers in recent years. Along with a simultaneous diversification in the demand for agricultural produce, this has generated steady growth in the demand for vegetables grown using reduced amounts of agricultural chemicals and for organic vegetables. In Western countries, organic vegetables have already gained an unassailable position in the market, and the quantities being distributed by major supermarket chains are expanding. Retail stores usually have a section for organic fruits and vegetables, and it is now easier than ever for consumers to purchase organic produce. In Japan, however, while the output of organically grown produce continues to increase each year, the actual market share remains very small (less than 1%). Even with the inclusion of cultivars grown with

reduced quantities of agricultural chemicals, it is still not easy for consumers in Japan to choose organic or reduced-chemical products.

At agricultural production sites, damage to fruits and vegetables caused by insects that are increasingly becoming resistant to pesticides are a growing problem. Large numbers of insect pest species have acquired resistance to pesticides and even to neonicotinoids, which have been used in an increasing number of pesticide formulations since the 1990s. This problem has become more severe by the growing number of insect species that have developed resistance to multiple pesticides, with different modes of action. Consequently, only a limited number of pesticides are effective, and it is becoming ever more difficult to eliminate small insect pests, such as thrips or aphids, using chemical pesticides.

In this situation, the development of insect pest control techniques that can replace or supplement chemical pesticides has become a pressing issue that requires the attention of researchers and technicians involved in pest control.

Why "light pest control" now?

Chemical pesticides have the ability to quickly and completely eliminate insects within the application range; thus, it is not easy to develop alternative pest control technologies with the same level of effectiveness. There is a need for integrated pest management (IPM) to control the density of insect pests through combinations of various available measures, while reducing the use of chemical pesticides. This means using a combination of biological, chemical, cultural, and physical pest control technologies in ways that do not interfere with each other, while taking the natural environment that surrounds agricultural land and the population dynamics of insect pests into consideration. The goal is to keep insect pest damage below the level at which economic consequences become a problem (economic injury level). Reducing the amount of chemical pesticides and the frequency of use is also expected to curb the emergence of pesticide resistance.

It has been over 50 years since IPM was first promoted and a wide range of technologies has been developed. Biological pest controls now established at production sites include the use of the entomopathogenic bacterium *Bacillus thuringiensis* and the introduction of natural insect enemies, such as *Amblyseius swirskii*. Against this background, technologies employing physical pest control,

especially “light pest control”, are expected to become tools for use in IPM. For example, traps using fluorescent tubes (black light) and moth-repelling lamps using yellow sodium lamps were developed as light pest control technologies in the 1990s, but there were few variations and there were limitations on where and how they could be used. However, the 2000s brought enormous changes. Light-emitting diodes (LEDs) capable of emitting monochromatic light with high luminous efficiency were developed, and mass production made them increasingly cheaper; thus increasing their potential for use in pest control. Simultaneously, improvements in techniques for examining insect neurophysiology, such as the spectral sensitivity of the retina, enabled a great deal of research to be conducted on the reactions of different insect species to exposure to light at different wavelengths. This led to the discovery of a new biological phenomenon, the light response reactions (Fig. 1). Advances in this area of research in recent years have been astonishing, resulting in the emergence of new pest control tools.

Basic principles of light pest control : Response reactions of insects to light and color

Light pest control utilizes the response reactions of insects to light and color (light response reactions). The color and shape of objects (or light sources) are detected by the ommatidia, which number from several hundred to several thousand in a compound eye. This sensory information is processed as electrical signal inputs by neural networks in the brain, and the ultimate output is manifested as behavioral or developmental changes. A well-known example of an insect light response reaction is the “phototaxis” of insects that swarm around streetlights. Research to date has identified a variety of other responses (outputs) to light in addition to phototaxis (Fig. 1).

Attraction, also known as “positive phototaxis”, is the response of moving toward a light source. Different species of insects are known to show preferences to different wavelengths and intensities of light, with the term “spectral preference” used to refer to the wavelength that is especially preferred by an insect (Fig. 2). This is an important factor when considering pest control technologies. Many insects have three photoreceptor genes coding for ultra-violet receptors with an absorption maximum in the region of 350 nm, blue photoreceptors in the region of 450 nm, and green photoreceptors in the region of 550 nm. The specific combination of these receptors determines the spectral sensitivity of the compound eye, and the spectral preference is

often in the region of the absorption maximum of ultra-violet or green receptors. Capture devices such as light traps or sticky sheets work on the principle of spectral preference.

Avoidance, also known as “negative phototaxis”, is the response of moving away from a light source. Coleoptera and other species that bore into the stems or fruits of plants have the behavioral trait of avoiding light and seeking hiding places. The wavelength and intensity of the light that produces this avoidance effect appears to differ depending on the species. Installing lights that insect pests avoid at the entrance to a cultivation facility would be expected to prevent invasions, and the direct illumination of crops should reduce the density of pests.

Light adaptation: The compound eyes of nocturnal moths, such as adult tobacco budworms, become accustomed to darkness (dark adaptation), and these insects become more active at night. When lighting is provided at night, light shining on the insect compound eye is reflected as a cat’s eye, but the reflection disappears very quickly. The compound eye changes to its daytime condition and light is no longer reflected. This is called “light adaptation”. Light and dark adaptations occur as a result of the movement of pigment granules within photoreceptor cells, and behaviors in nocturnal insects such as flying, mating, and egg-laying cease completely when the insect is in a state of light adaptation.

Circadian rhythms: Like humans, insects also have internal clocks in the brain, and the physiological status and timing of various behaviors are determined by the light-dark cycle of day and night. The biological clock cells in the brain and other central nervous systems that govern these behaviors are reset if light is shone on the insect during the night, causing the biological clock to be reset. This forward or backward shift is called a “phase shift”, and it causes the timing of activities such as flying or courtship to be thrown into confusion. Shining a light for a certain period of time (~ a few hours) at cultivation facilities can cause disturbances in these activities.

Photoperiodicity: To survive the winter, insects need to suspend their activities and endure the cold by entering a period of dormancy. Many insects take the shortening day length in autumn as a cue to prepare for winter by inducing dormancy. If insects are exposed to light at night for several successive days during this period, the induction of dormancy will be disturbed and the insects will be unable to survive the winter.

Light toxicity: Near-ultraviolet light is known to have a strong cytotoxic effect. It can not only denature proteins, but can also induce mutations by damaging double-stranded DNA in the cell. Some insect species are known to experience a breakdown in the cytoarchitecture of the compound eye upon exposure to ultraviolet or blue light. Light toxicity may also be expressed as a developmental impairment or behavioral disorder. Utilizing the damaging action of light on insects shows promise for use in pest control technologies in plant production sites and food factories.

Masking (or camouflaging): By manipulating the visible components of the light used to illuminate crops, the colors and patterns of objects can become difficult for insects to discriminate. For example, shining a blue light on apples will cause them to appear blackish. Many insects have a high sensitivity to near-ultraviolet rays, and their vision is therefore blocked if they are exposed to light that is lacking the ultraviolet range. Covering the facility with a film that shields ultraviolet rays can prevent the invasion of pests into cultivation facilities; thus, camouflaging the crops inside the facility so that insects cannot easily see them.

Dorsal light reaction: When locusts or dragonflies fly, ambient light (direct light from the sun or scattered light from the atmosphere) impacting the dorsal side of their bodies helps the insects to maintain the correct body angle and to keep level flight, horizontally. Placing a sheet of a material with a high optical reflectance across the ground reflects sunlight upward, which impairs the normal flying behavior of these insects. Mulching sheets for weed control made of a white material with high optical reflectance would likely be effective in preventing the invasion or settling of these insect pests.

Edge reaction: Many insects move toward the boundary region of a dark and light surface due to phototaxis. This is probably the effect of the visual contrast, but an edge can be created not only by a difference in light and dark, which is a difference in light intensity, but also by differences in the wavelength components or in the polarization orientation. Incorporating visual contrast into the design of light traps or sticky sheets is therefore expected to improve capture efficiency.

It can be seen from these examples that there is great diversity in the light response reactions of insects and that these responses are highly species-specific (Fig. 1). The stimuli are dependent not only on the intensity of the light, but are also greatly influenced by factors such as the wavelength, combination of wavelength components

(wavelength distribution), method of illumination (the size of the light source and the angle of illumination), background brightness and color contrast, and the presence or absence of polarization. In addition to the complexity of the stimuli, the insect itself may have inherent reactions that are species-specific, which may differ depending on the developmental stage (larva or adult) and physiological condition (fully fed or fasting state). The individual internal clock is also an important factor, and differences can arise due to diurnal, nocturnal, or crepuscular control cycles. The timing of active behaviors such as flying, courtship, and feeding vary by species. Therefore, to develop effective light pest control technologies, it is first necessary to characterize the reactions of the target insect species, and then full consideration needs to be given to such conditions as the materials used as a light source (bulbs, LEDs, etc.), the shape of the lighting system, and the installation site.

Technological development of light pest control

The main light pest control technologies developed to date utilize the light response reaction (classified in Fig. 3). Here, we review the latest information regarding these control methods.

Among the technologies that exploit the attraction of insects to light, electric insect zappers using black light are widespread. Black light contains near-ultraviolet light and therefore effectively attracts a variety of insect pests. These devices are useful not only in agriculture, but also for eliminating sanitary insect pests. The spectral preferences of various insect species have been determined (Fig. 2), making it possible to target specific species with captures and killing technologies that use LED light sources. Insects that are strongly attracted to near-ultraviolet light (365–385 nm) include the southern green stink bug, which damages wetland rice and vegetables; the brown planthopper, which is a vector of viral diseases in rice; the Ceratopogonidae, which are vectors for the arbovirus that causes damage to livestock; the tobacco beetle, which damages stored dry foods; and the rice leaf bug, which causes spotted rice damage. Similarly, irradiating water basin traps with ultraviolet rays (365 nm) is effective for attracting and killing fungus gnat species. Yellow tea thrips, which damage tea and citrus fruits, are strongly attracted to green light (520 nm). The flower bug (*Orius sauteri*) and mirid bug (*Nesidiocoris tenuis*), which are predatory enemies of thrips, and the tachinid fly (*Exorista japonica*), which is a parasitic enemy of thrips, have been

discovered to have a “unique” spectral preference for purple light (405 nm) (Fig. 4). Because thrips and whiteflies are attracted to ultraviolet and green light, it may be possible to use purple light to selectively attract the predators of pest insects to agricultural areas. Pest control methods using these techniques for field cultivated eggplants and greenhouse cultivated tomatoes have been demonstrated (Fig. 5).

To attract diurnal insect pests, methods using colored sticky sheets (adhesive traps) are more effective than nighttime light exposure. As the daytime use of reflective materials has been developed for different insect species, materials with the necessary properties to reflect specific regions of sunlight to target different insect pest species have also been developed. Melon thrips, a major insect pest of fruit and vegetables, are most effectively captured with blue or cobalt green (spectral reflectivity peak wavelength 503 nm) sticky sheets, while western flower thrips are effectively captured and killed with ultraviolet (355 nm) and green light (525 nm). Trials have recently been conducted in which visual contrasts are applied to sticky sheets to increase insect capture efficiencies through the use of patterns of light and shade using black and white materials.

Many insects were long believed to be unable to see red light (600–700 nm), and it was noticed only recently that brown planthoppers display a slight attraction to red light (660–735 nm). Although the mechanism behind the behavior has not yet been fully clarified, thrip density was reportedly suppressed in the presence of red light (600–660 nm). This has proven to be extremely effective in controlling thrips in eggplants and melons, and considerable progress has been made in its implementation. Based on the response reaction to red, not only red lighting but also red nets, the red light has been effectively used to control thrips species, and the rate of parasitism of outdoor cultivated green onions by onion thrips was decreased with the use of red nets. Manipulating the color of the strands of the nets has been shown to make them more effective for preventing the invasion of thrips and whiteflies into cultivation facilities.

The use of yellow fluorescent lamps to control owlet moths, a type of sucking insect that damages eggplants and peaches, was introduced in the 1990s and has become widespread as a technology for controlling nocturnal moth species. In the cultivation of ornamental flowers, the larvae of the owlet moth species rather than the adults cause damage to leaves and buds. Yellow fluorescent lamps suppress flying and egg-laying activities in adults, and the larvae of species such as the tobacco cutworm in roses and

cotton bollworm in carnations can be similarly controlled. The outdoor cultivation of crops such as lettuce requires a large area, and protection is offered by just a few light sources. High-intensity sodium lamps have been developed to meet this need, and highly efficient high-intensity LEDs are also being considered. The cotton bollworm and the cabbage moth have a high spectral sensitivity to green light (500–550 nm), and this has been shown to effectively control their behavior. Thus, similarly to the use of yellow fluorescent lamps, illumination with green LEDs has also been incorporated into IPM systems for outdoor vegetable cultivation.

Photoirradiation for specific periods of time has been conducted to affect the behaviors controlled by circadian rhythms (Fig. 1), but the observed effects are more delayed than those observed for light adaptation. A few hours of photoirradiation after sunset causes mating behavior to be thrown out of sync in the smaller tea tortrix, a major insect pest of tea. It has been discovered that blue light (around 450 nm) is effective at disrupting the circadian clock, and progress is being made in the development of LED light sources that control mating behavior by disrupting circadian rhythms.

With regard to light toxicity, ultraviolet rays are known to cause cellular injury, while some insect species such as leaf-miner flies have been found to be highly sensitive to blue light (400–470 nm), which inhibits development and causes death. Because this method can kill pests using light in the visible range (without the use of ultraviolet light), it has the potential to be widely used for killing pests in plant production sites and food factories.

The use of films that cut near-ultraviolet rays as pest control methods are based on the principle of masking (Fig. 1). Behavioral analysis using the greenhouse whitefly has clarified the principles of pest control by cutting near-ultraviolet rays. When plastic greenhouses are covered with a film that cuts near-ultraviolet rays, there is no change in the speed of their movement and dispersal within the greenhouse, but invasions from the outside are suppressed, while movement from inside the greenhouse to outside is promoted. Similarly, scattering a fine white calcium carbonate powder on the leaves of citrus trees to disguise their color is likely to be an effective method for masking plants from insects.

The dorsal light and edge reactions are used in methods that disrupt the flight of insect pests (Fig. 1). With regard to the dorsal light reaction, a silvery-white

polyethylene film was introduced as a measure to protect vegetables from the arrival of winged aphids, and its use has spread to the protection of tomatoes and other vegetables from thrips and whiteflies. High-performance, non-woven fabrics made of polyethylene with improved optical reflectance, vapor permeability, insulating properties, and durability have now been developed. The effectiveness of flight disruption by these reflective sheets has been demonstrated not only to control the invasion of small insect pests into cultivation facilities, but also for suppressing the density of pests on crops. With regard to the edge reaction (Fig. 1), studies of the arrival sites on flat LED light sources show that many insect species react to visual contrasts when determining their flight routes. A colored sticky sheet can be used to create a visual contrast using a black and white pattern for shade and light, and this visual contrast can be incorporated into flat light sources not only by controlling the brightness of the light source panels, but also by manipulating the wavelength or polarizing the light to create differences in brightness. A more effective capture can be expected from conventional traps if a visual contrast is incorporated.

Thus, light pest control development has progressed to exploiting insect life cycle phenomena or control methods that no one predicted would be used just 10 years ago. While there are high expectations for these new pest control technologies, the adaptive significance and the active mechanisms of light response reactions are not yet fully understood, and they need to be theoretically proven (Fig. 1). The accumulation of research on topics such as the range over which insect pests are affected by light control measures may lead to the development of practical pest control technologies. In addition, light pest control is likely to be useful for controlling sanitary insects in food factories or retail stores because no chemical products are used. There is interest in developing air cleaners that incorporate mosquito repellant functionality, and light pest control is expected to have applications in domestic insect control devices as well.

Key points when introducing light pest control technology

Light pest control technologies are described in detail in each section of this special feature, but as these are new technologies there are some key points that should be noted prior to introducing them into cultivation systems (Fig. 3). The first key point is that none of these technologies have the same effectiveness as chemical pesticides. For example, experiments in the control of thrips using illumination with red light

(vegetables grown in a greenhouse) have shown a reduction in density of 90–95%, indicating that complete elimination of the insect pests is not achieved. Also, although natural enemies can be attracted with red LEDs, and the density of thrips can then be brought down to fewer than 10%, a density reduction of only 60% is achieved during their peak in summer. This means that light pest control technologies need to be carefully combined with other pest control measures to mitigate the risk of economic damage. The second key point is that even for the same crop, there will be regional differences in cultivation methods, climate conditions, and crop diseases. It is therefore necessary to investigate methods of light pest control that take into account the combination of these conditions. For example, with regard to the use of technology to attract natural enemies of thrips using purple LEDs (Fig. 4), insectary plants first need to be established to attract flower bugs (*O. sauteri*) within the environment in which their predatory effect is needed (Fig. 5). If this preparation is inadequate, the purple LEDs cannot be expected to be effective as a pest control measure. Care needs to be taken to ensure the selection of an insectary plant that suits the particular area and the arrangement of LEDs in the field. Red nets have been highly effective at preventing pest invasions in cultivation facilities, but it is essential that the nets be placed at the invasion entry point at an early stage.

Successful cultivation of crops also requires the management of fertilizer, water, temperature, and various other aspects. When a new technology, such as light pest control, is introduced, it is also necessary to manage the risk of reducing pesticide use, and agricultural producers need to display good judgment developed through years of experience. Furthermore, to reliably realize the effectiveness of light pest control, the cooperation of specialists involved in providing technical guidance and dissemination of information will be essential.

CONCLUSION

Pesticide resistance among insect pests was first reported in the 1950s, shortly after the introduction of chemical pesticides. Given the high selection pressure of chemical pesticides, it is probably fair to say that this problem was bound to occur. Various insect pests have been reported to develop resistance, even to neonicotinoid pesticides, which are comparatively new agents, and there is a never-ending game of cat-and-mouse between the development of new pesticides and the acquisition of tolerance to them.

The “light pest control” technologies presented here exploit the instinctive nature of insects (Fig. 1; Fig. 3), and while selective pressure (pest control efficiency) is not strong, resistance to light pest control measures is unlikely to appear. In addition, light pest control technologies can easily be combined with other pest control measures, such as the use of natural predators (Fig. 4; Fig. 5), allowing a variety of use patterns. Our investigations will continue, with the cooperation of other parties involved in light pest control, to achieve our goal of ensuring that new light pest control technologies will play a role in low-pesticide-use cultivation systems, and thus reduce the environmental burden of pesticide residues.

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LITERATURE CITED

1. Antignus, Y, Ben-Yakir, D. 2004. Ultraviolet-absorbing barriers, an efficient integrated pest management tool to protect greenhouses from insects and virus diseases. p. 319-335. In: *Insect Pest Management*, Springer.
2. Ben-Yakir, D., Antignus, Y., Offir, Y., Shahak, Y. 2013. Optical manipulations: an advance approach for reducing sucking insect pests. p. 249-267. In: *Advanced Technologies for Managing Insect Pests*, Springer.
3. Briscoe, A. D., Chittka, L. 2001. The evolution of color vision in insects. Ann. Rev. Entomol. 46:471-510.
4. Hori, M., Shibuya, K., Sato, M., and Saito, Y. 2014. Lethal effects of short-wavelength visible light on insects. *Scientific Reports*, Article number: 77383. Avaiable from: doi.org/10.1038/srep07383
5. Hironaka, M., Sekine, T., Miyamoto, T. and Masuda, T. 2018. Perspective of light traps in agricultural use: improvement of trap efficiency based on visual edge effects. Plant Prot. 72:182-191.

6. Ishikawa, R., Doi Makoto, Nakano, R., and Katayama, H. 2018. Efficacy of red light irradiation for controlling *Thrips palmi* in greenhouse melon cultivation. Plant Prot. 72:155-157.
7. Johansen, N. S., Vänninen, I., Pinto, D. M., Nissinen, A. I., Shipp, L. 2011. In the light of new greenhouse technologies: 2. Direct effects of artificial lighting on arthropods and integrated pest management in greenhouse crops. Ann. Appl. Biol. 159:1–27.
8. Mainali, B. P., Lim, U. T. 2010. Circular yellow sticky trap with black background enhances attraction of *Frankliniella occidentalis* (Pergande) (Thysanoptera: Thripidae). Appl. Entomol. Zool. 45:207–213.
9. Ogino, T., Uehara, T., Yamaguchi, T., Noro, C., Maeda, T., Shimoda, M. 2015. Spectral preference of the predatory bug *Orius sauteri* (Heteroptera: Anthocoridae). Jpn. J. Appl. Entomol. Zool. 59:10–13.
10. Ogino, T., Uehara, T., Muraji, M., Yamaguchi, T., Ichihashi, T., Suzuki, T., Kainoh, Y., Shimoda, M. 2016. Violet LED light enhances the recruitment of a thrip predator in open fields. Scientific Reports 6, Article number: 32302. Available from: doi: 10.1038/srep32302.
11. Ogino, T., Uehara, T., Yamaguchi, T., Kainoh, Y., Shimoda, M. 2018. Attraction tool of predatory bugs by violet LED. Plant Prot. 72:27-30.
12. Sato, Y. 2018. A new control method against the smaller tea tortrix, *Adoxophyes honmai*, using blue LED Lights. Plant Prot. 72:16-21.
13. Shimoda, M., Honda, K. 2013. Insect reactions to light and its applications to pest management. Appl. Entomol. Zool. 48:413–421.
14. Shimoda, M. 2018. Recent progress in physical insect pest control using light and color. Plant Prot. 72: 3-8.
15. Tokumaru, S., and Ito, S. 2018. Control effect of new type red collor nets on small pests. Plant Prot. 72: 158-161.
16. Tokushima, Y., Uehara, T., Yamaguchi, T., Arikawa, K., Kainoh, Y., Shimoda, M. 2016. Broadband photoreceptors are involved in the violet light preference in the parasitoid fly *Exorista Japonica*. *PLoS ONE* 2016 Aug 17; 11(8): e0160441. Available from: doi: 10.1371/journal.pone.0160441.
17. Uehara, T., Yamaguchi, T., Kotaki, T., Shimoda, M. 2014. Evaluation of Phototactic Behavior by Two-dimensional Open field test in the brown-winged green bug, *Plautia stali* (Scott) (Hemiptera: Pentatomidae). Jpn. J. Appl. Entomol. Zool. 58:36–38.
18. Yase, J. 2018. Characteristics of greenhouse insect orientations to the color sticky trap and its use. Plant Prot. 72:177-181.

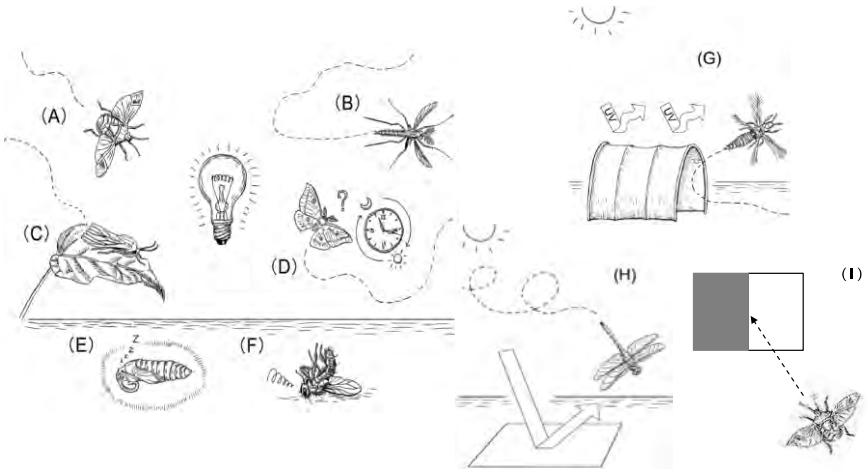

Fig. 1. Various light response reactions of insects (A) Attraction, (B) avoidance, (C) light adaptation, (D) circadian rhythms, (E) photoperiodicity, (F) light toxicity, (G) masking, (H) dorsal light reaction, and (I) edge reaction. Adapted with modifications from Shimoda and Honda (2013). Many aspects of the mechanisms of light response reactions have not yet been determined and the conceptual understanding of these responses may change in the future.

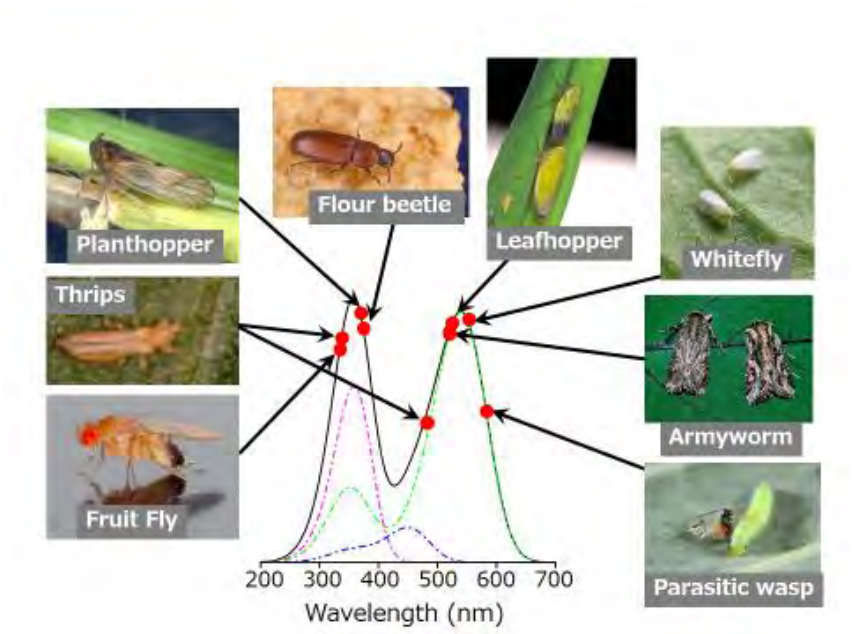

Fig. 2. Light wavelengths that attract insects (spectral preferences). Light of different wavelengths with the same intensity (brightness) was used to determine the spectral preferences of each insect species tested. The sensitivity spectrum of the insect compound eye has peaks in the ultraviolet region (around 350 nm), the green region (around 550 nm), or in both, and many insects exhibit a preference for these regions. This figure shows an example of a bimodal mean sensitivity spectrum, with peaks in both the ultraviolet and green regions. Most insects are attracted to UV or green light. These correspond to the peaks of photosensitivity, determined by an electroretinogram (ERG).

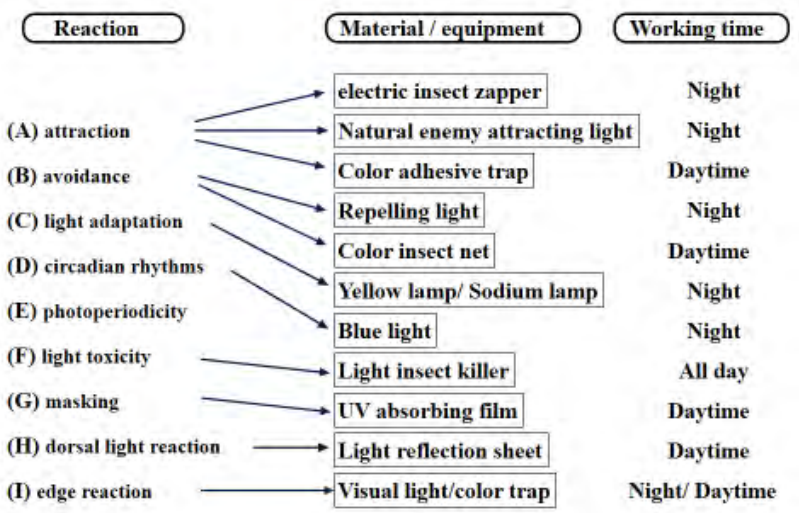

Fig. 3. Insect pest control technologies using light response reactions. The arrows show the relationship between the main pest control materials that use light response reactions and their underlying principles. Pest control materials based on entirely new concepts may well be developed in the future as a result of research findings regarding light response reactions and technological developments.

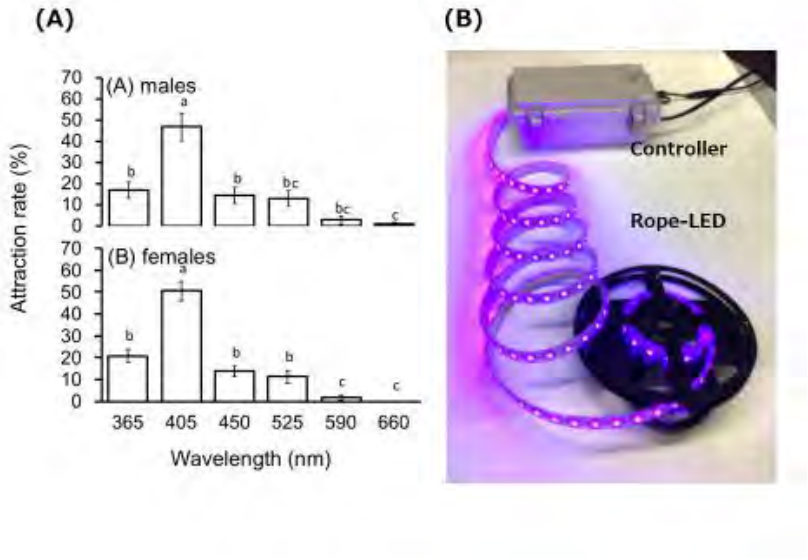

Fig. 4. Predatory bug, *Orius sauteri*, shows a unique spectral preference for violet light. (A) Adult *O. sauteri* were most attracted to violet light of 405 nm, although this wavelength is just at the bottom of the photosensitivity curve. This was the first finding of an insect being predominantly attracted to violet light. (B) An LED-lighting device attracting *O. sauteri* was developed.

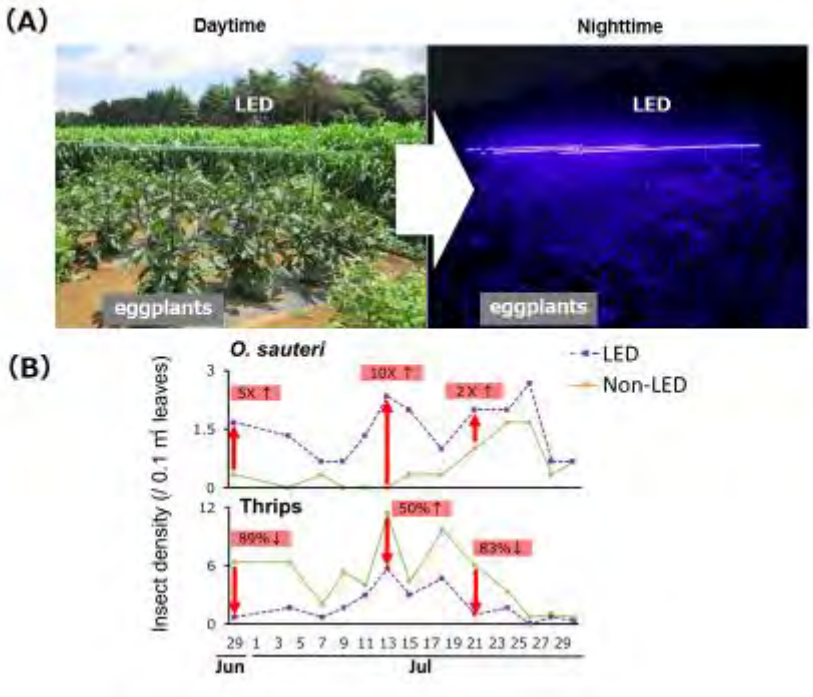

Fig. 5. Introduction of violet-LED lighting into open-field eggplant cultivation

(A) A rope-type violet-LED was installed above the eggplants. The eggplants were cultivated according to conventional farming methods in central Japan, but no pesticides were used so that the effectiveness of LED-lighting alone could be assessed. The intensity of the LED light was very low (1/4,000 of sunshine intensity). Lighting was limited to 3 h in the evening when *O. sauteri* are active. (B) The insect density on eggplants was compared between LED illuminated and non-LED illuminated plots. In the LED plots, the *O. sauteri* density immediately increased when lighting commenced and remained higher than in the non-LED plots. The thrips density was always lower than in the non-LED plots. The thrips density was suppressed to an almost economically acceptable level. The effective control of thrips using violet-LED lighting was confirmed.